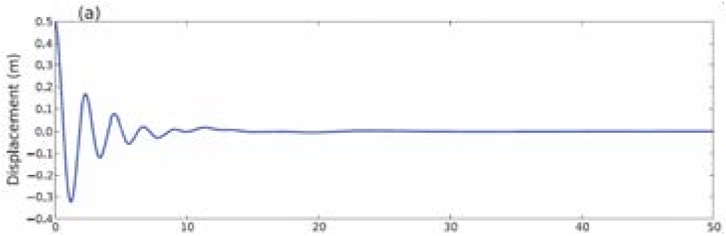
Numerical Wave Tank testing for Marine Renewable Energy Devices Part 2

Dr Josh Davidson

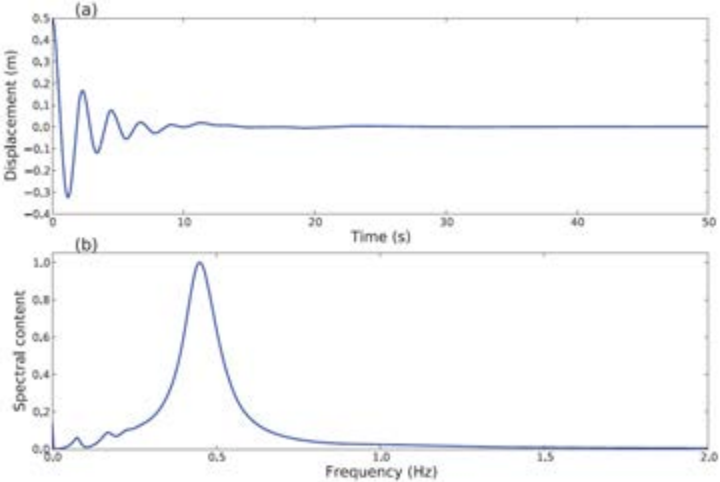
June - 2025

Outline

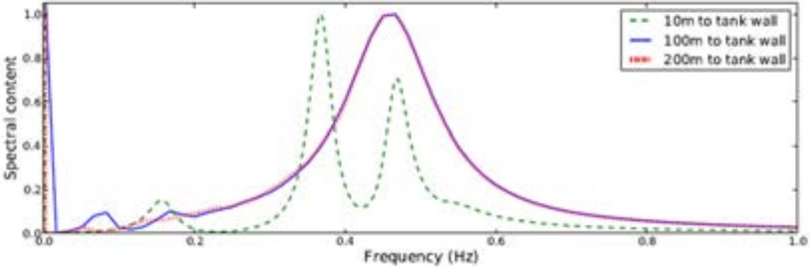
- Free Decay Experiments
- Input Force
- Wave driven motion
- Moorings
- Currents
- Wind turbines
- Machine Learning



[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016



[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016


10m to tank wall
100m to tank wall
200m to tank wall
Spectral content
Frequency (Hz)
0.0
0.2
0.4
0.6
0.8
1.0

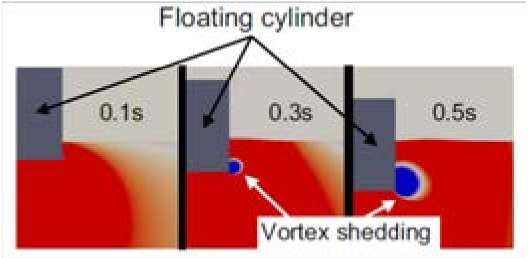
Types

Types

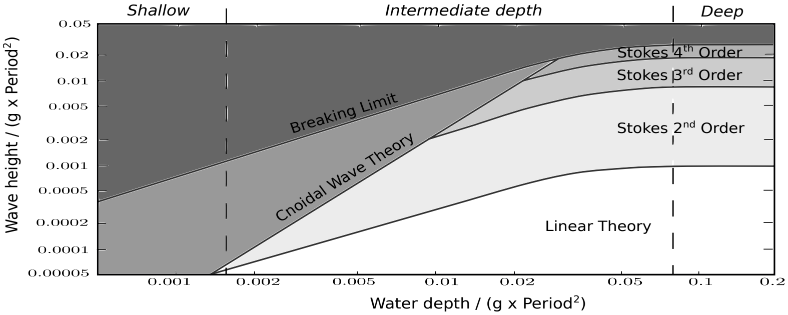
- Viscosity
- Nonlinear ocean waves
- Time-varying wetted body surface

Viscosity

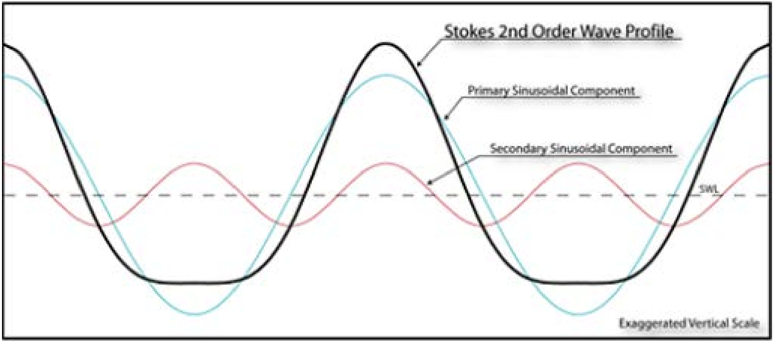
- Viscosity gives rise to drag forces, resulting from pressure/form drag and skin friction drag.
- For WECs, pressure drag is the main contributor and skin friction is typically negligible. Pressure drag is caused by flow separation and vortex shedding, whose force on the WEC is nonlinear, increasing quadratically with the relative WEC-water velocity.



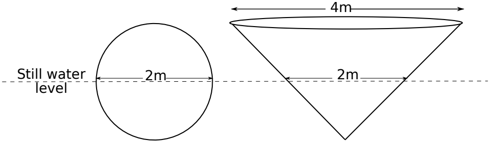
[1] Davidson, Giorgi and Ringwood, *Linear parametric hydrodynamic models for ocean wave energy converters identified from numerical wave tank experiments*, Ocean Engineering, 2015

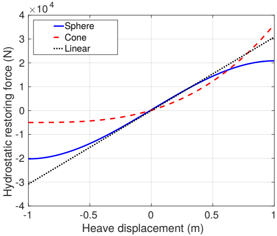


[1] Le Mehaute, B. An Introduction to Hydrodynamics and Water Waves; Springer Science & Business Media: Berlin/Heidelberg, Germany, 1976.

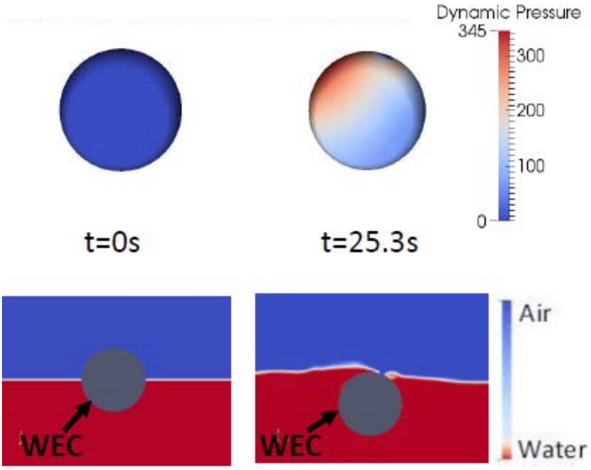

Stokes 2nd Order Wave Profile
Primary Sinusoidal Component
Secondary Sinusoidal Component
SWL
Exaggerated Vertical Scale

Equilibrium position and geometries of example sphere and cone

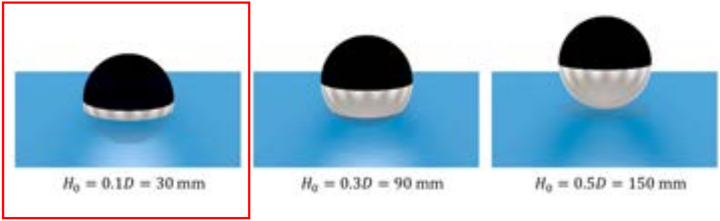




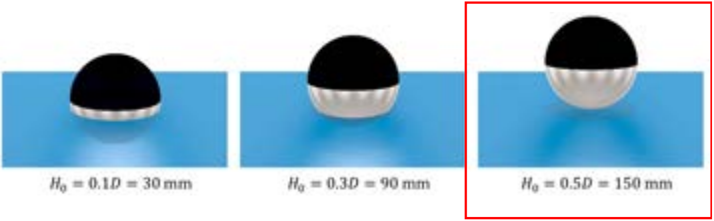
[1] Davidson and Costello, *Efficient nonlinear hydrodynamic models for wave energy converter design - A scoping study*, Journal of Marine Science and Engineering (Special Issue "Nonlinear Numerical Modelling of Wave Energy Converters"), 2019



[1] Davidson, Windt, Giorgi, Genest and Ringwood, *Evaluation of Energy Maximising Control Systems for WECs using OpenFOAM*, OpenFOAM - Selected papers from the 11th Workshop, 2019

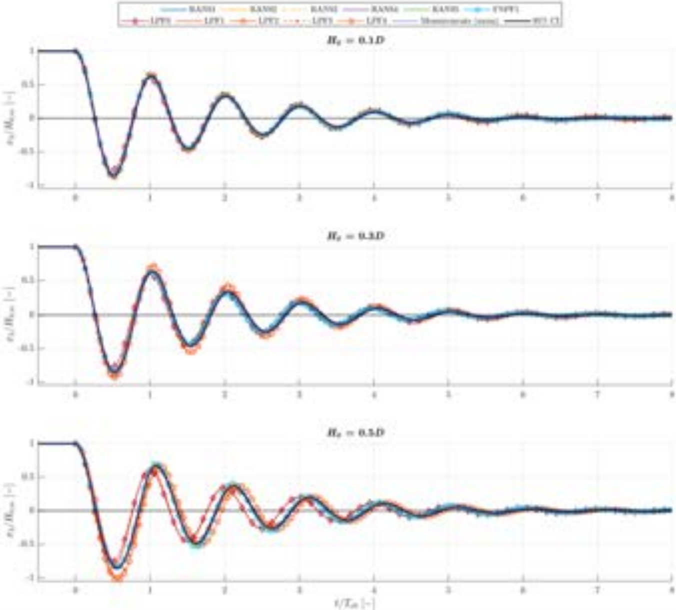


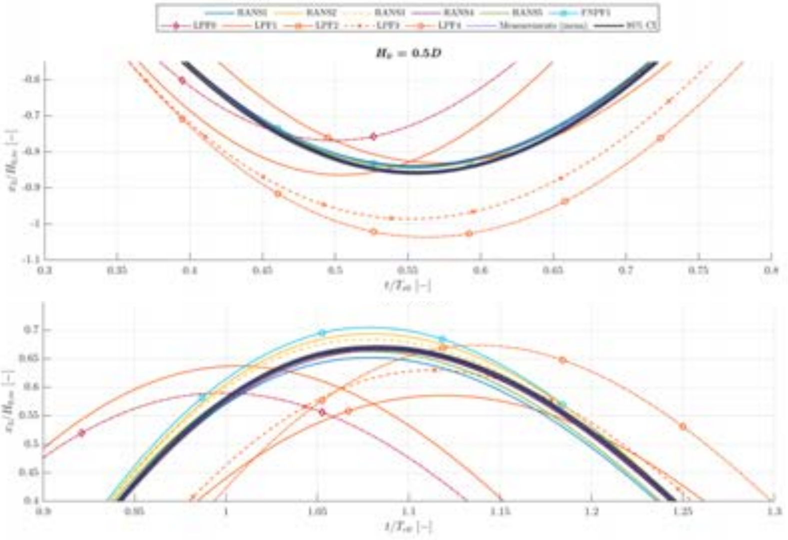
$H_0 = 0.1D = 30$ mm
$H_0 = 0.3D = 90$ mm
$H_0 = 0.5D = 150$ mm


$H_0 = 0.1D = 30$ mm
$H_0 = 0.3D = 90$ mm
$H_0 = 0.5D = 150$ mm

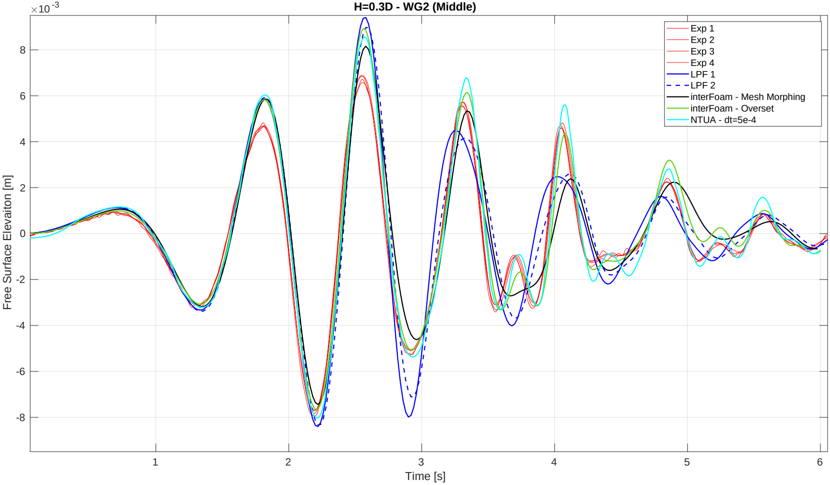
Free Decay of a Sphere

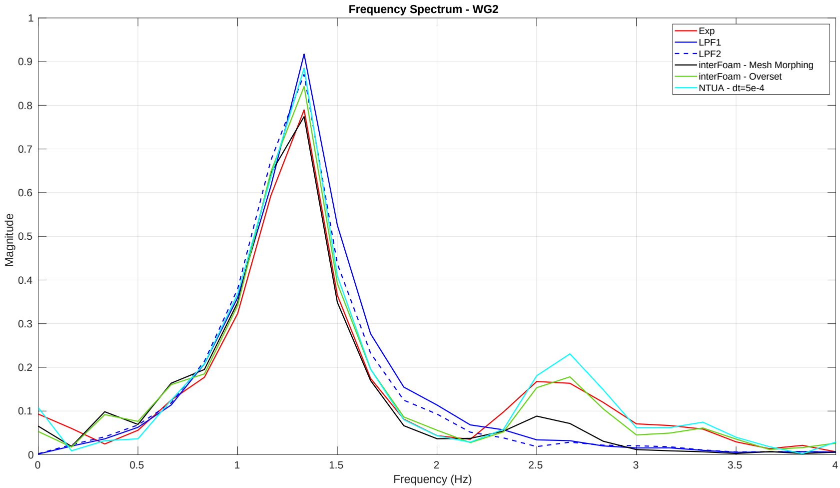
Benchmark comparison



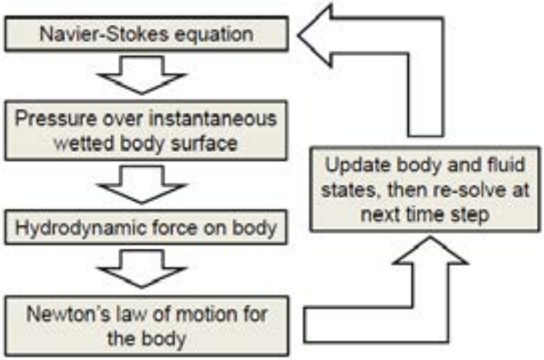


[1] Kramer et al, *Highly Accurate Experimental Heave Decay Tests with a Floating Sphere: A Public Benchmark Dataset for Model Validation of Fluid-Structure Interaction*, Energies, 2021

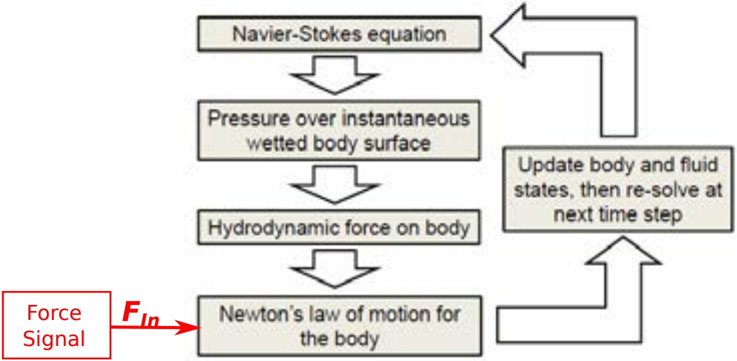

H=0.3D - WG2 (Middle)
×10 -3
8
6
4
2
0
-2
-4
-6
-8
Free Surface Elevaiton [m]
1
2
3
4
5
6
Time [s]
Exp 1
Exp 2
Exp 3
Exp 4
LPF 1
LPF 2
interFoam - Mesh Morphing
interFoam - Overset
NTUA - dt=5e-4

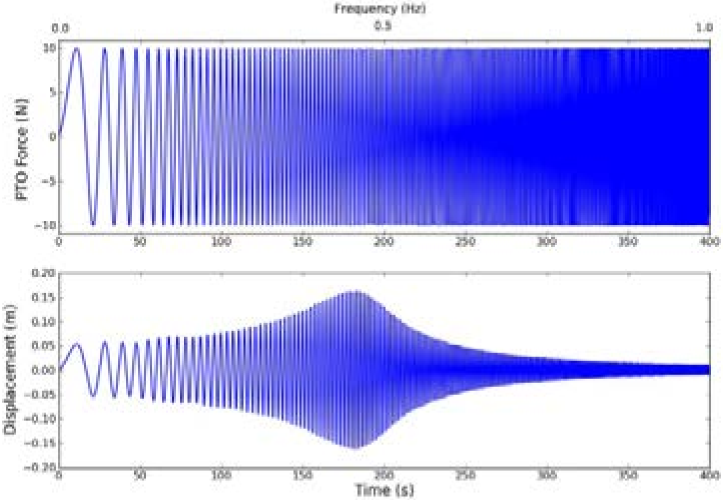

Frequency Spectrum - WG2
Exp
LPF1
LPF2
interFoam - Mesh Morphing
interFoam - Overset
NTUA - dt=5e-4
Magnitude
Frequency (Hz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3
3.5
4

Input Force

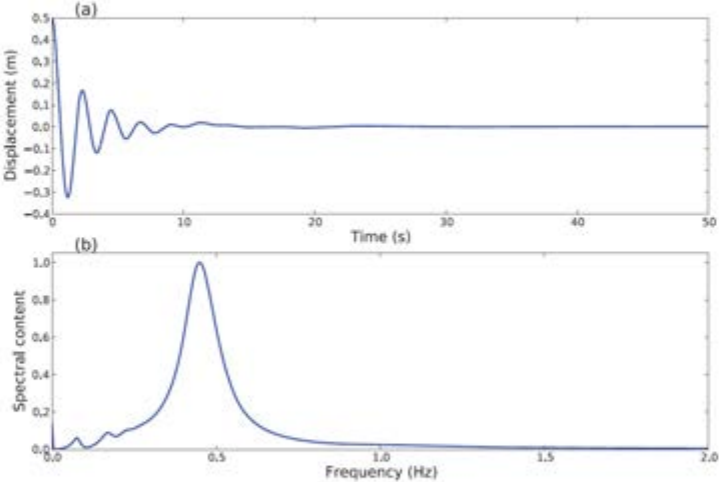


Navier-Stokes equation
Pressure over instantaneous wetted body surface
Hydrodynamic force on body
Newton's law of motion for the body
Update body and fluid states, then re-solve at next time step


Navier-Stokes equation
Pressure over instantaneous wetted body surface
Hydrodynamic force on body
Newton's law of motion for the body
Update body and fluid states, then re-solve at next time step
Force Signal
F_{In}



[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016



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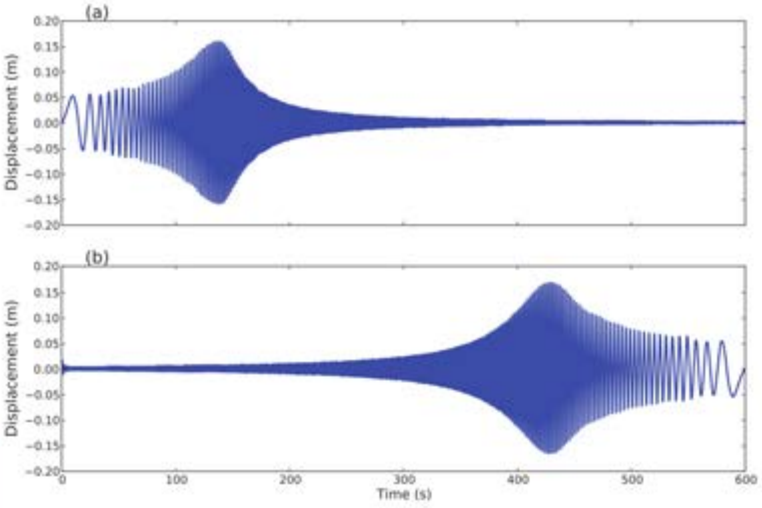

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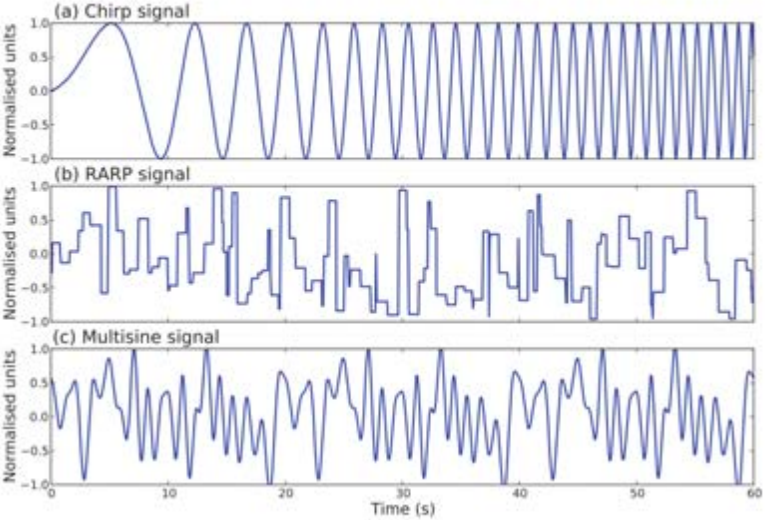
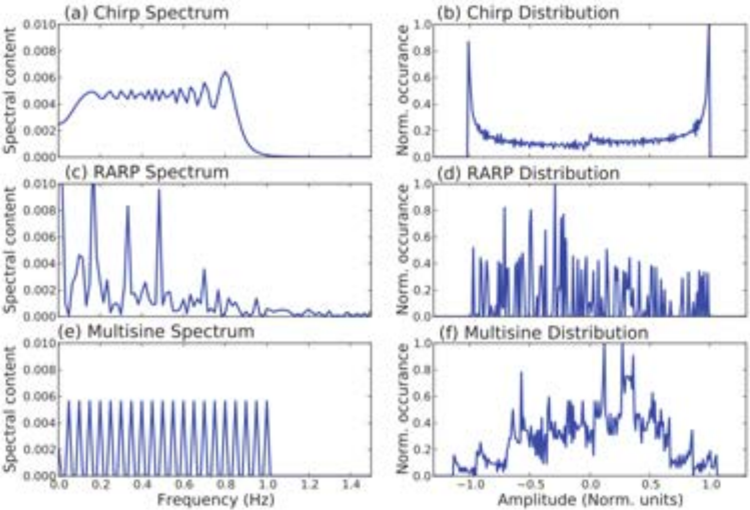
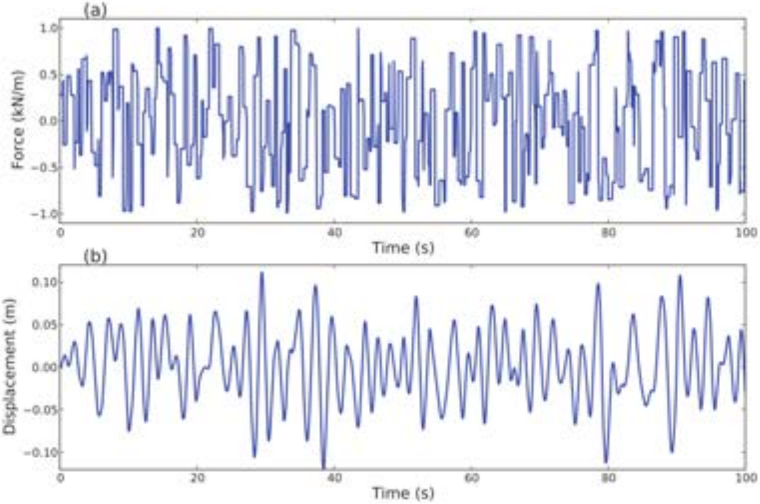


[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016

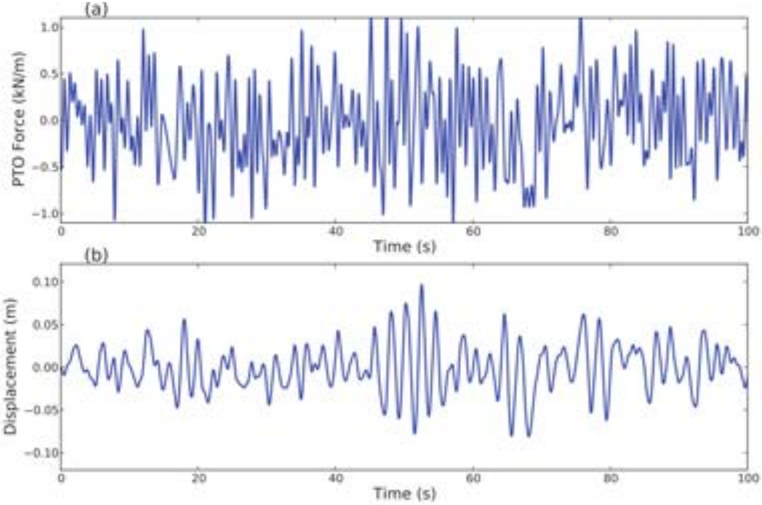


[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016

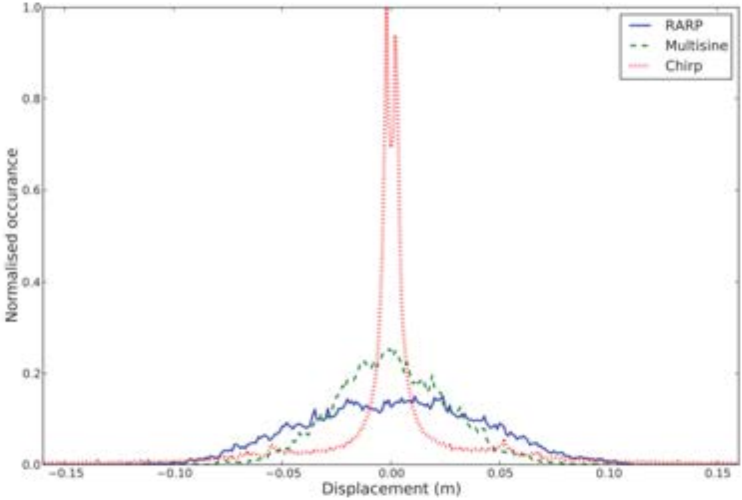
Input Force
RARP Signal



[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016

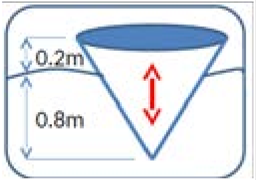


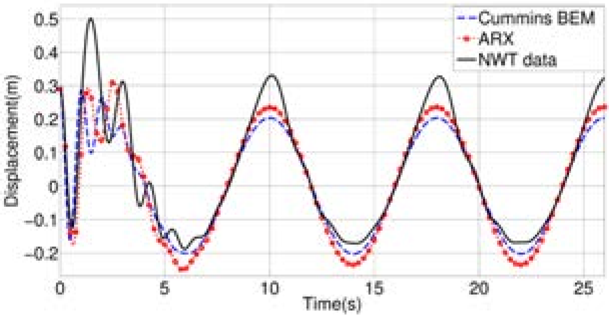
[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016



[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016

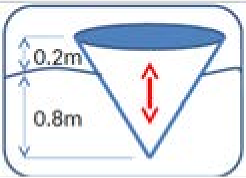
Sinusoidal input PTO force : Amplitude 960N

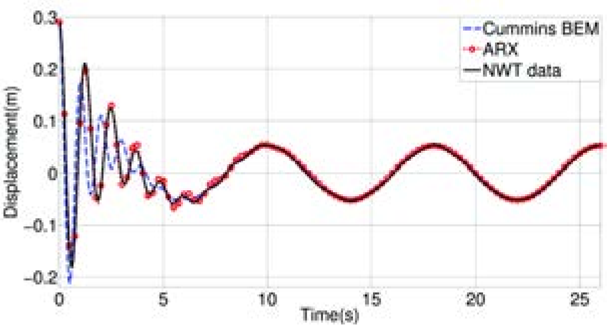




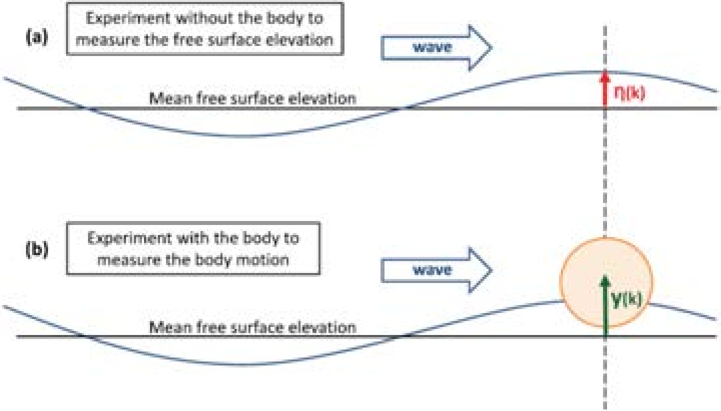
[1] Davidson, Giorgi and Ringwood, *Numerical wave tank identifcation of nonlinear discrete time hydrodynamic models*, 1st RENEW Conference, 2014

Sinusoidal input PTO force : Amplitude 240N





[1] Davidson, Giorgi and Ringwood, *Numerical wave tank identifcation of nonlinear discrete time hydrodynamic models*, 1st RENEW Conference, 2014



[2] Davidson, Giorgi and Ringwood, *Identification of wave energy device models from numerical wave tank data - Part 1: Numerical wave tank identification tests*, IEEE Transactions on Sustainable Energy, 2016

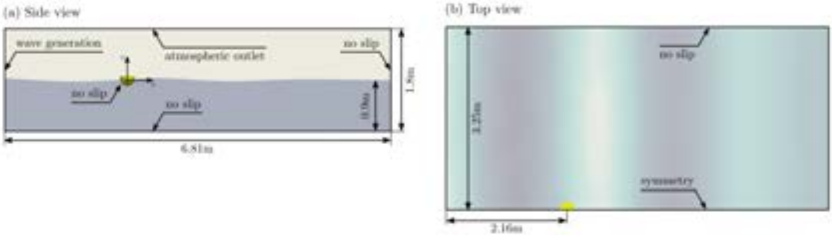
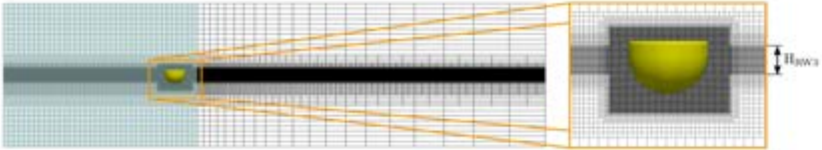
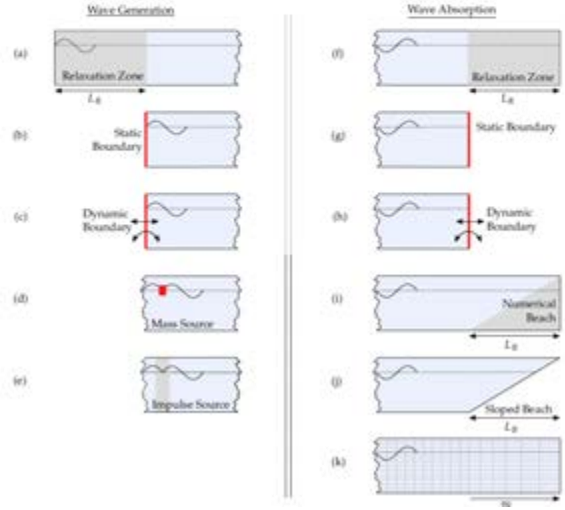


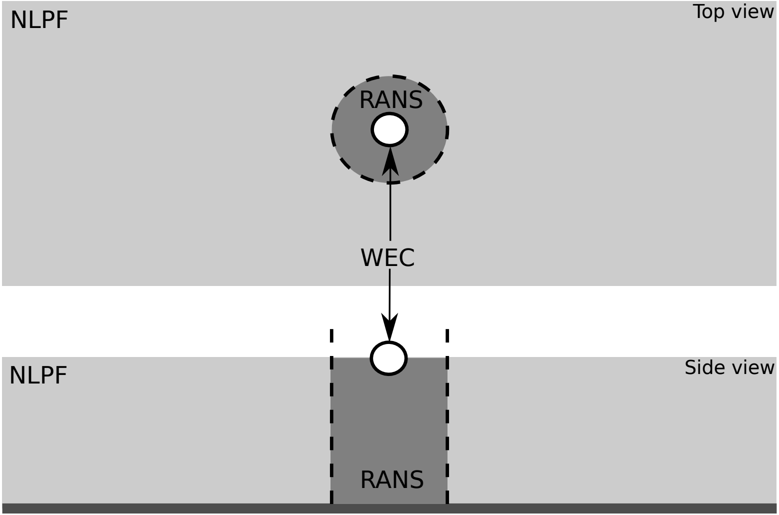
Figure 3. Schematic of the numerical wave tank: Side view (**a**) and top view (**b**).



[1] Windt, Faedo, Pena-Snachez, Davidson, Ferri and Ringwood, *Validation of a CFD-Based Numerical Wave Tank Model of the 1/20th Scale Wavestar Wave Energy Converter*, Fluids, 2020



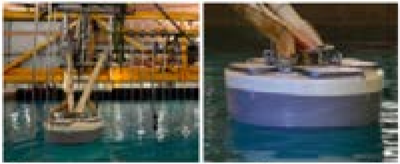
[1] Windt, Davidson, Schmitt and Ringwood, *On the Assessment of Numerical Wave Makers in CFD Simulations*, Journal of Marine Science and Engineering, 2019

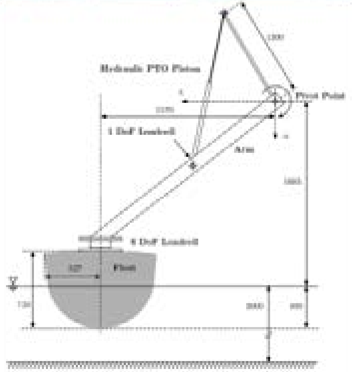


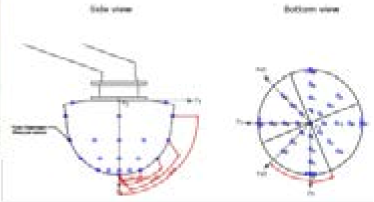
[2] Davidson and Costello, *Efficient nonlinear hydrodynamic models for wave energy converter design - A scoping study*, Journal of Marine Science and Engineering (Special Issue "Nonlinear Numerical Modelling of Wave Energy Converters"), 2019

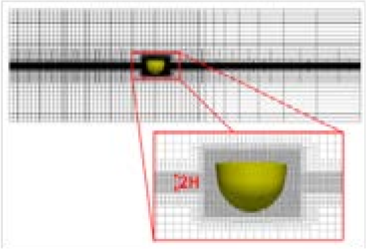
Input Waves

Wavestar Validation

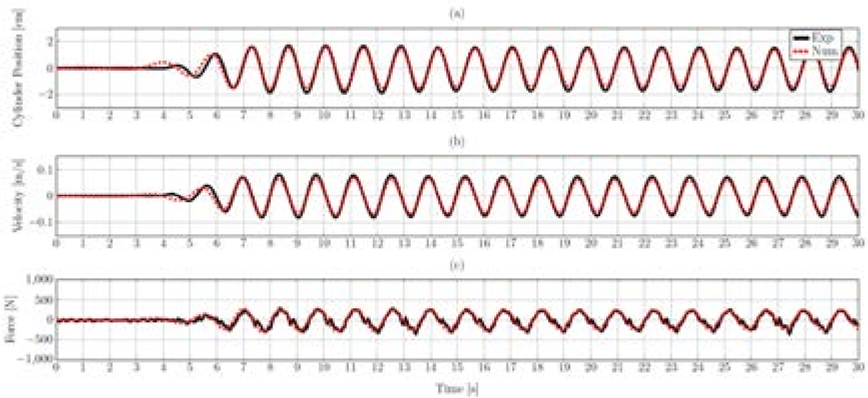








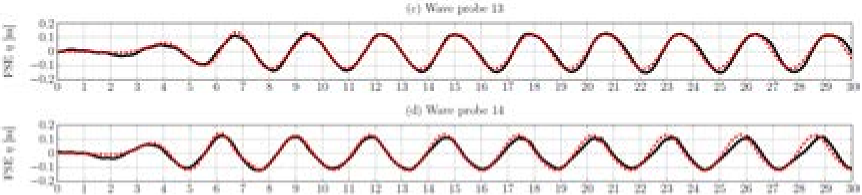
[1] Windt, Davidson, Ransley, Greaves, Jakobsen, Kramer and Ringwood, *Validation of a CFD-based numerical wave tank model for the power production assessment of the wavestar ocean wave energy converter*, Renewable Energy, 2020



[1]Windt, Davidson, Ransley, Greaves, Jakobsen, Kramer and Ringwood, *Validation of a CFD-based numerical wave tank model for the power production assessment of the wavestar ocean wave energy converter*, Renewable Energy, 2020

Question

What are some of the challenges/limitations in validating against physical wave tank data?



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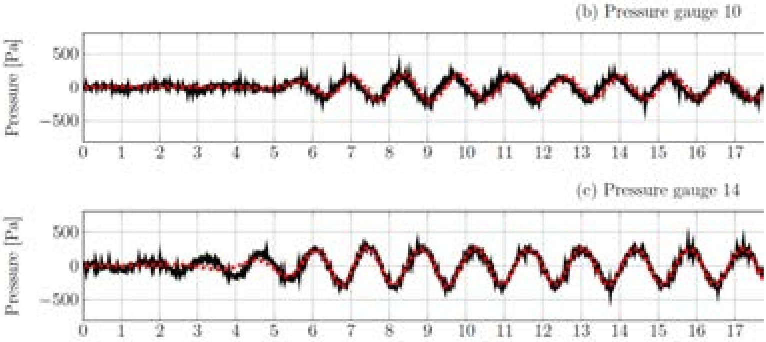

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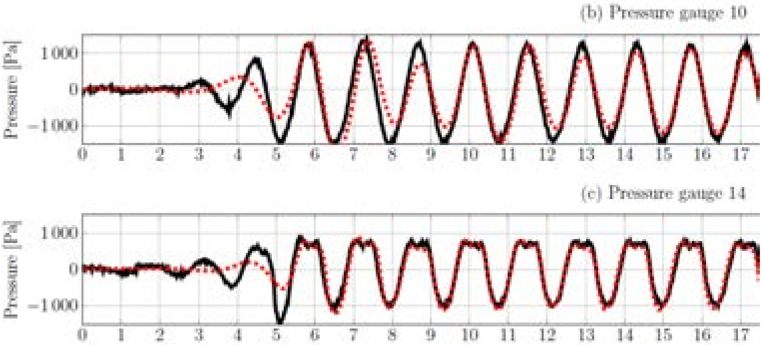
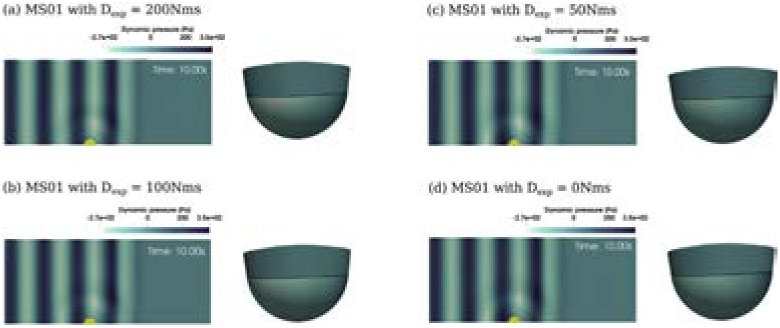


[1] Windt, Davidson, Ransley, Greaves, Jakobsen, Kramer and Ringwood, *Validation of a CFD-based numerical wave tank model for the power production assessment of the wavestar ocean wave energy converter*, Renewable Energy, 2020

Input Waves
Pressure measurements



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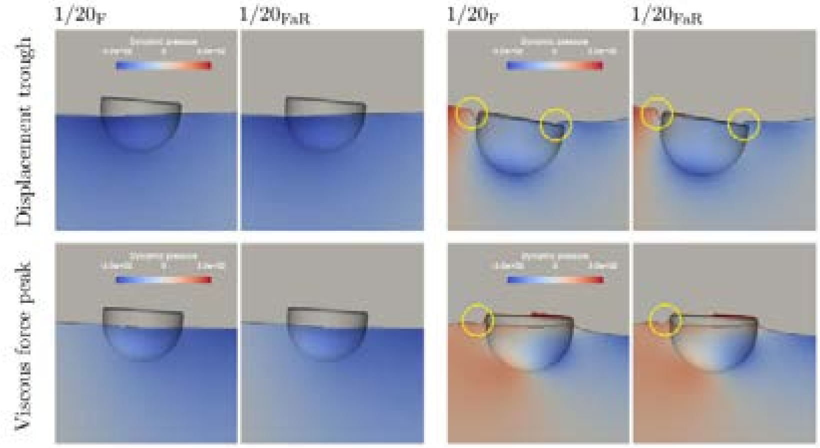
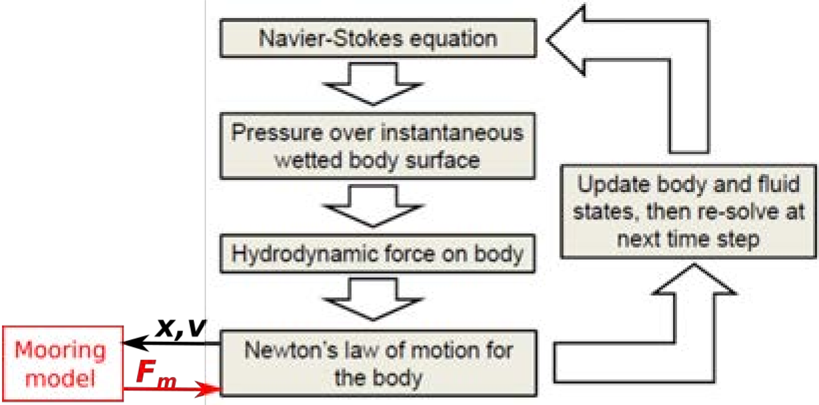
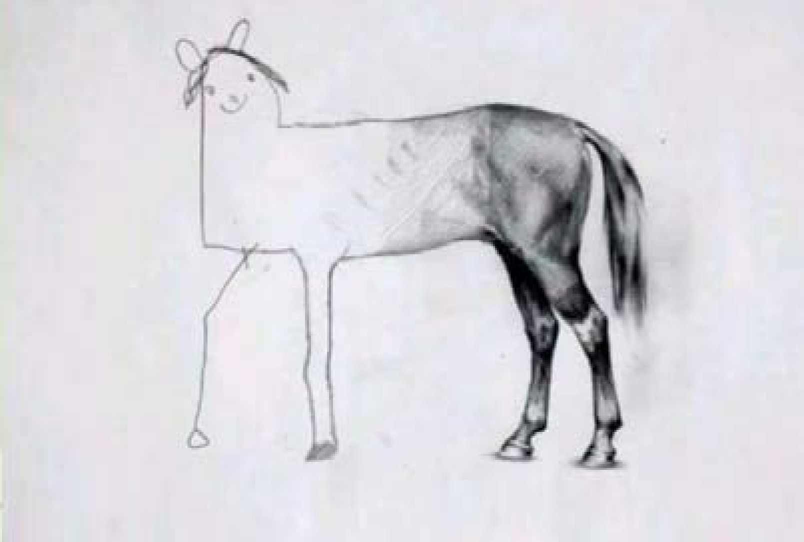
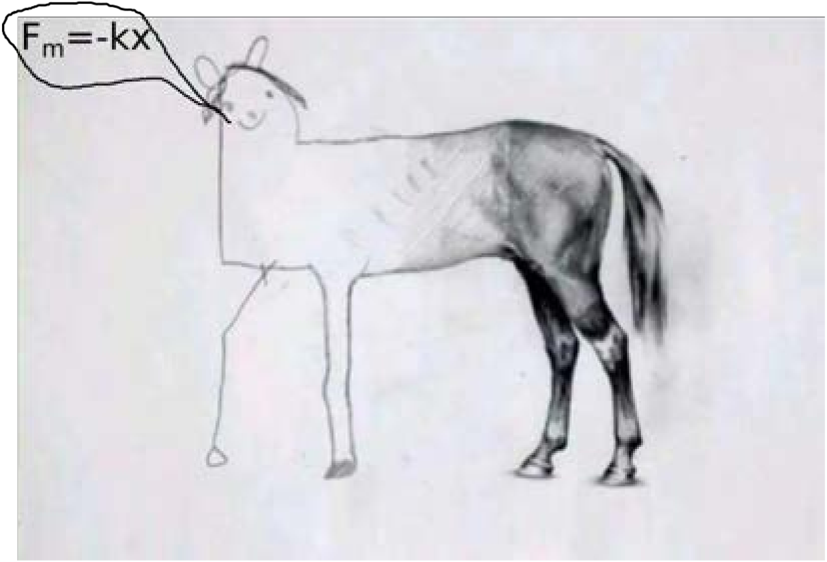


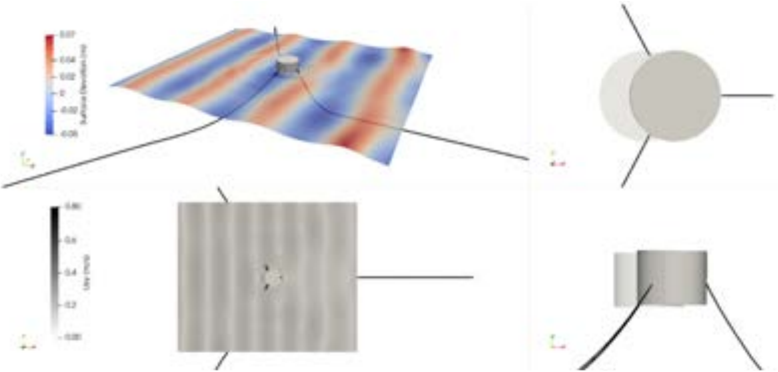
[1]Windt, Davidson and Ringwood, *Numerical analysis of the hydrodynamic scaling effects for the Wavestar wave energy converter*, Journal of Fluids and Structures, 2021

Moorings

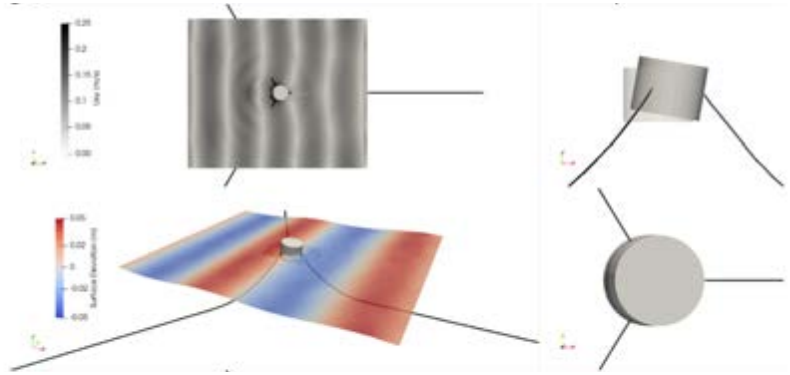

Navier-Stokes equation
Pressure over instantaneous wetted body surface
Hydrodynamic force on body
Newton's law of motion for the body
Update body and fluid states, then re-solve at next time step
Mooring model
x, v
F m




F_m=-kx



[1]Barajas, Lara, Davidson and Romano, *Porous medium-based PTO damping and overset mesh motion: A combined approach for effective OpenFOAM simulations of floating OWCs*, Applied Ocean Research, 2024



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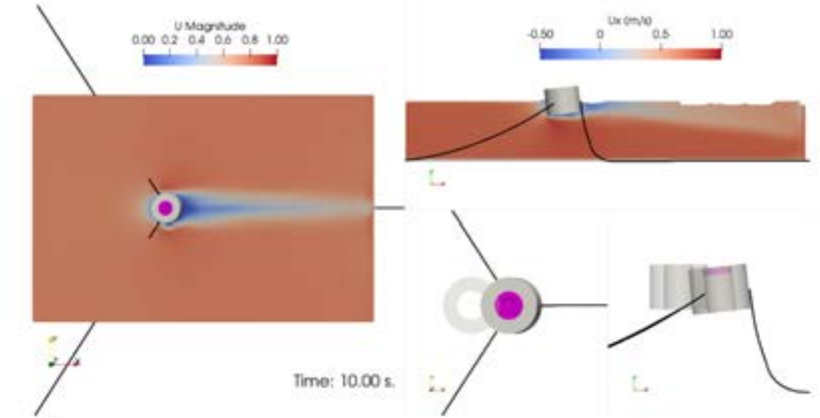

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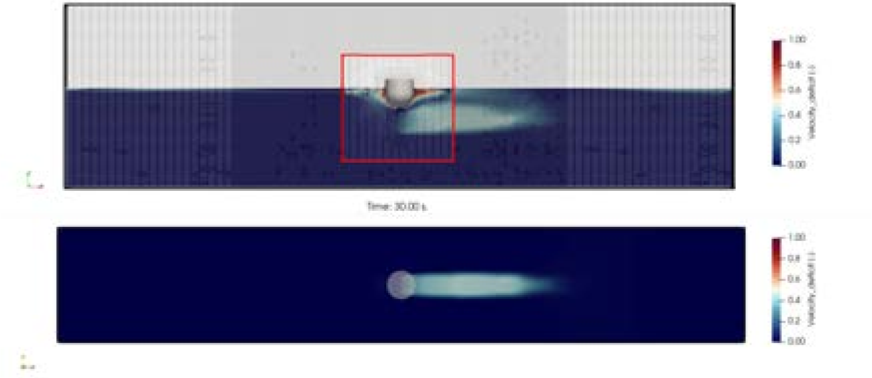
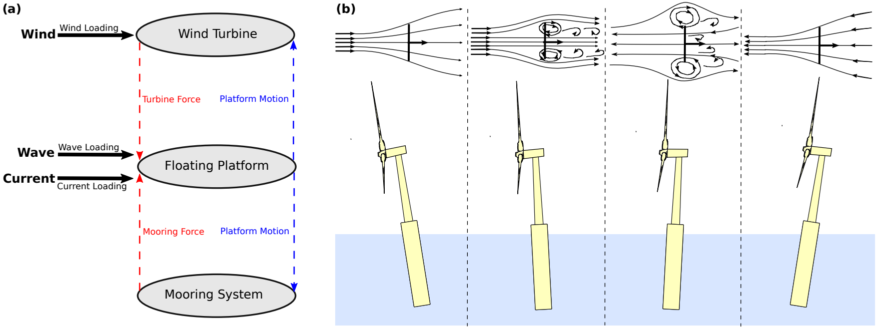


[1]Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025



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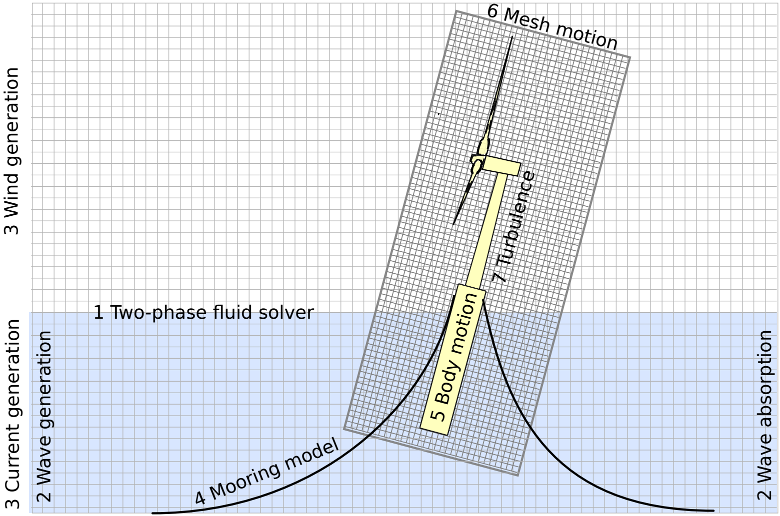
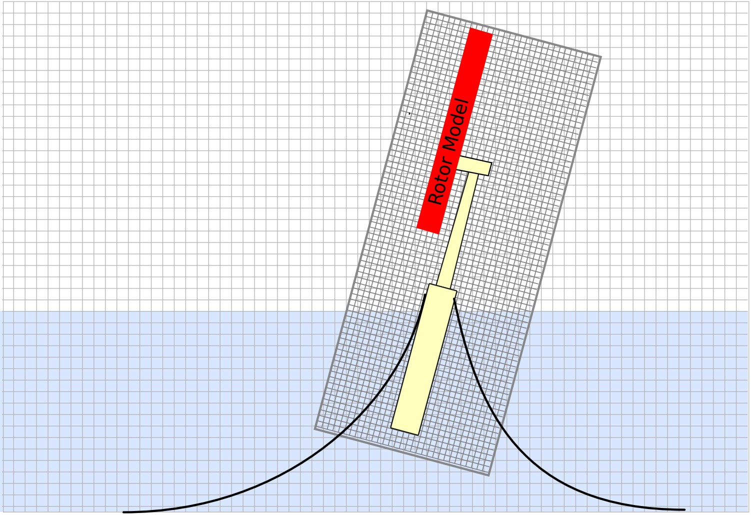


[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025

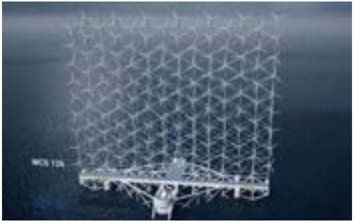
Floating Wind Turbine

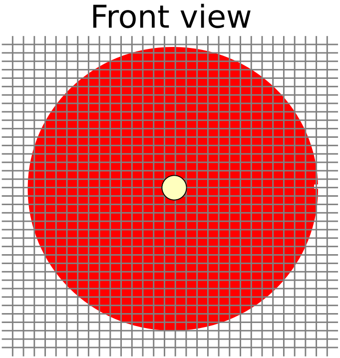
Rotor Modelling???

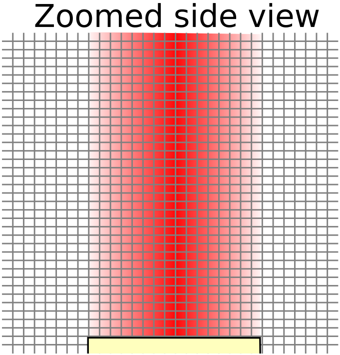


[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025

Floating Wind Turbine
Rotor Applications

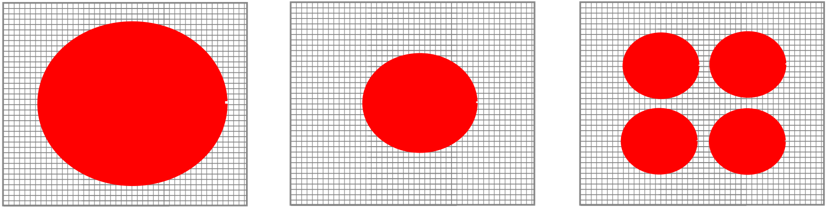






[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025

Easily adjust rotor characteristics — Multiple Rotors



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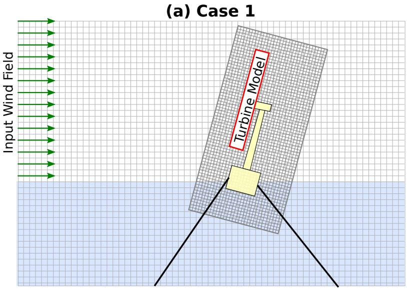
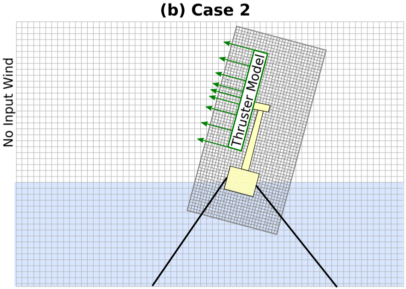
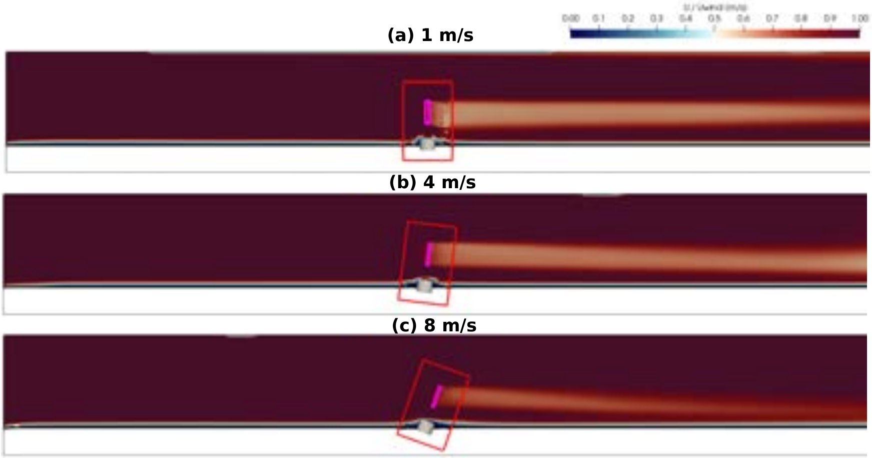
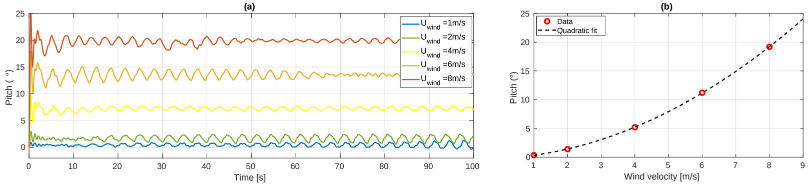


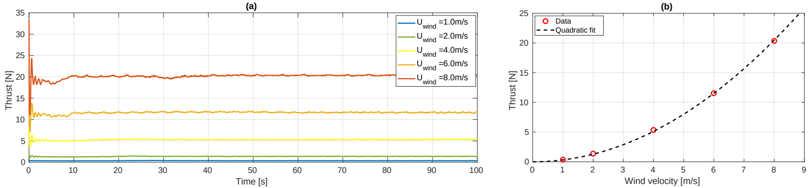


[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025

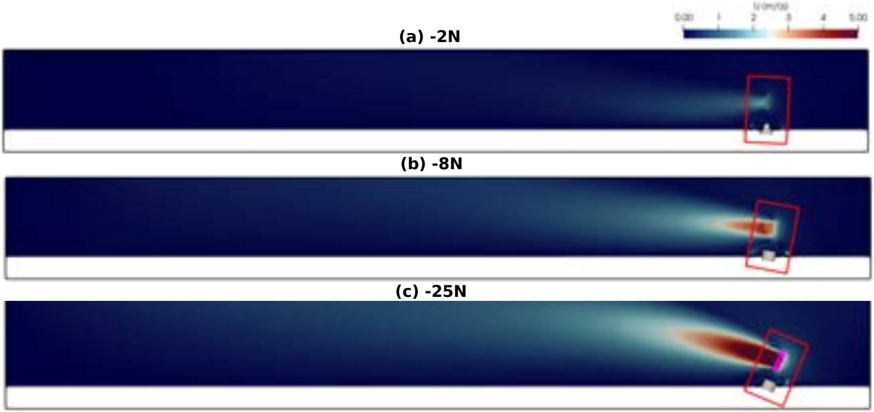


[1]Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025





[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025



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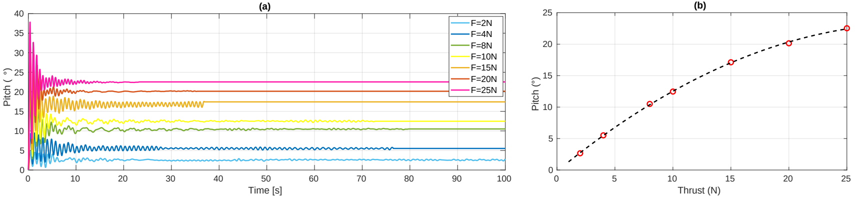
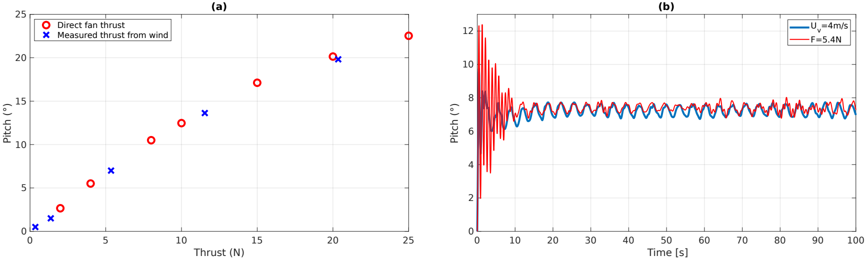


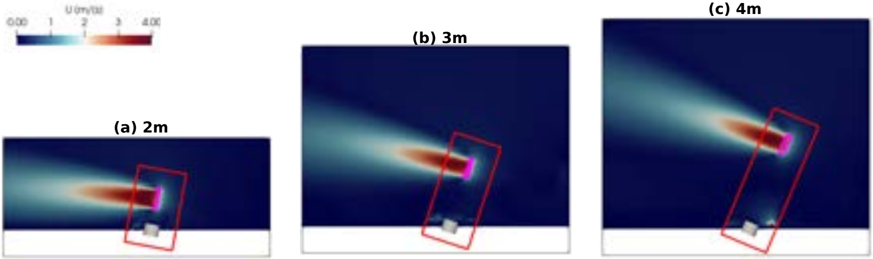
[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025



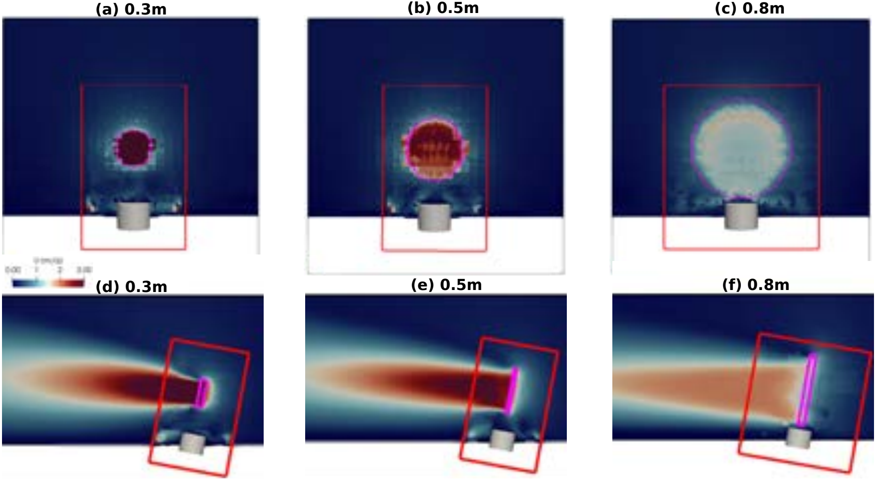
[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025

Floating Wind Turbine

Illustrative Example - Hub Height



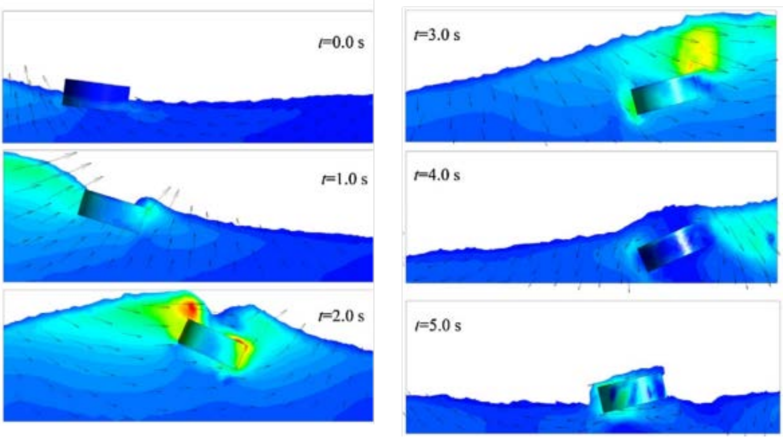
[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025



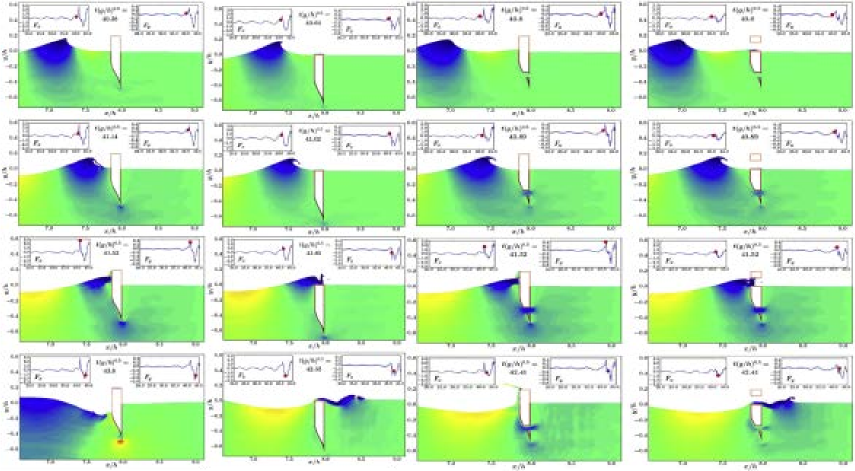
[1] Davidson, Barajas and Lara, *Turbines and Thrusters: A Versatile OpenFOAM Framework for Modeling Aerial Rotors on Floating Bodies*, In preparation, 2025

Question

Why is a NWT a good tool for Extreme/Survival Condition experiments?

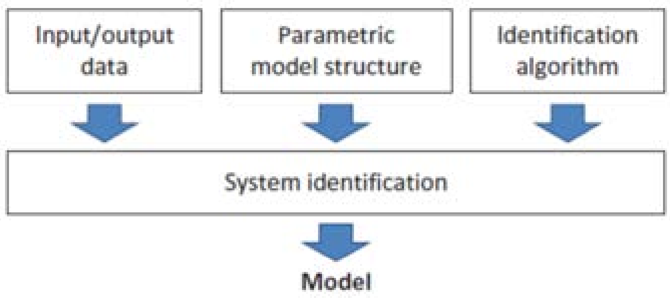


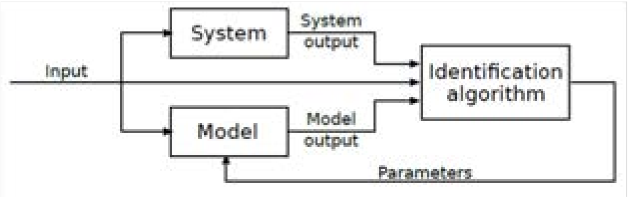
[2] Chen et al, *Numerical modelling of a point-absorbing wave energy converter in irregular and extreme waves*, Applied Ocean Research, 2017



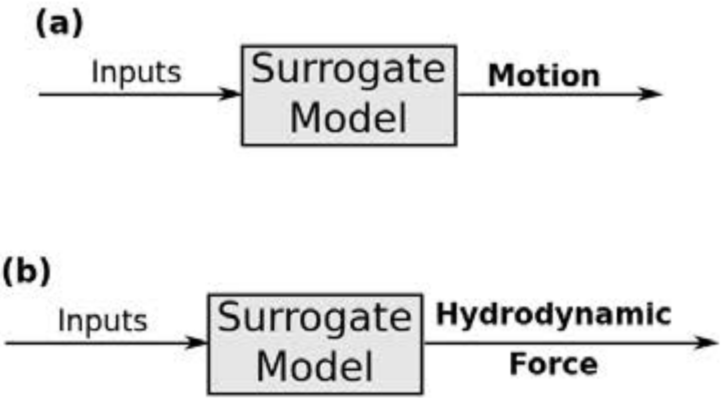
[2] Madhi and Yeung, *On survivability of asymmetric wave-energy converters in extreme waves*, Renewable Energy, 2018

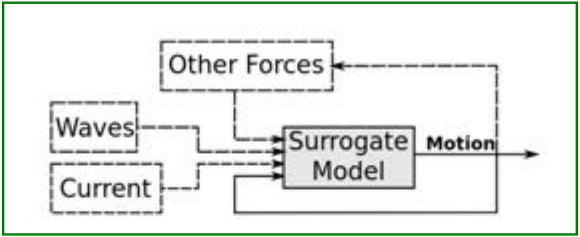
Machine Learning

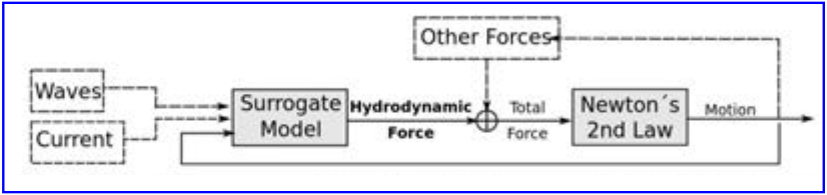


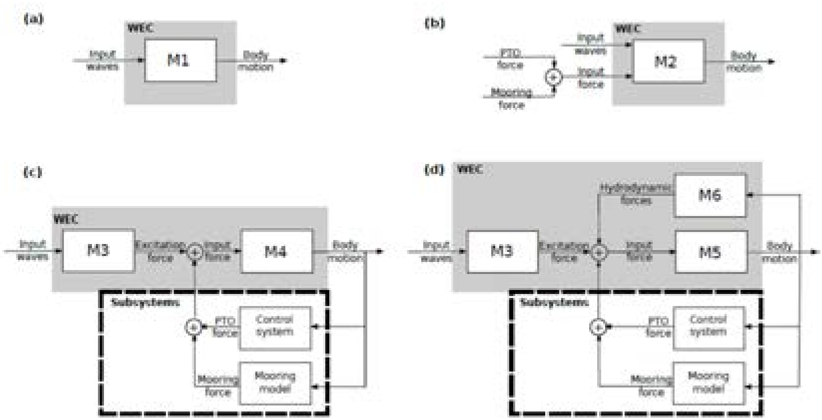


[1] Ringwood, Davidson and Giorgi, *Identifying models using recorded data*, Numerical Modelling of Wave Energy Converters : State-of-the-art for single devices and arrays, Academic Press, 2016

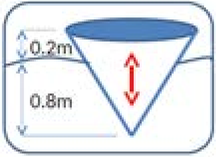

(a)
Inputs
Surrogate Model
Motion
(b)
Inputs
Surrogate Model
Hydrodynamic Force


Other Forces
Waves
Current
Surrogate Model
Motion


Other Forces
Waves
Current
Surrogate Model
Hydrodynamic Force
Total Force
Newton´s 2nd Law
Motion



[2] Davidson and Costello, *Efficient nonlinear hydrodynamic models for wave energy converter design - A scoping study*, Journal of Marine Science and Engineering (Special Issue "Nonlinear Numerical Modelling of Wave Energy Converters"), 2019

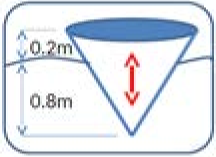


Nonlinear heave restoring force

$$(m+\mu_\infty)\ddot{x}_3(t) + \int_0^t K_r(t-\tau)\dot{x}_3(\tau)d\tau + f_s(x_3,t) = f_e(t)$$

$$(m+\mu_\infty)\ddot{x}_3(t) + \int_0^t K_r(t-\tau)\dot{x}_3(\tau)d\tau + \sum^{n} a_n x_3^n(t) = f_e(t)$$

[1] Davidson, Giorgi and Ringwood, *Numerical wave tank identifcation of nonlinear discrete time hydrodynamic models*, 1st RENEW Conference, 2014



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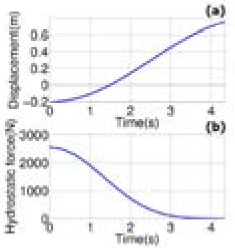
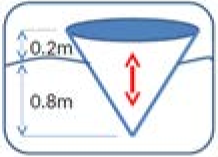


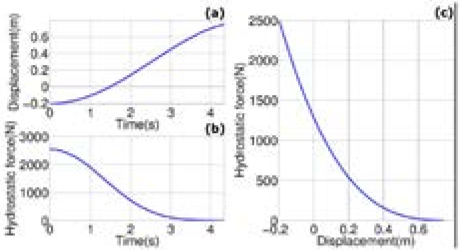
[1] Davidson, Giorgi and Ringwood, *Numerical wave tank identifcation of nonlinear discrete time hydrodynamic models*, 1st RENEW Conference, 2014

Nonlinear heave restoring force

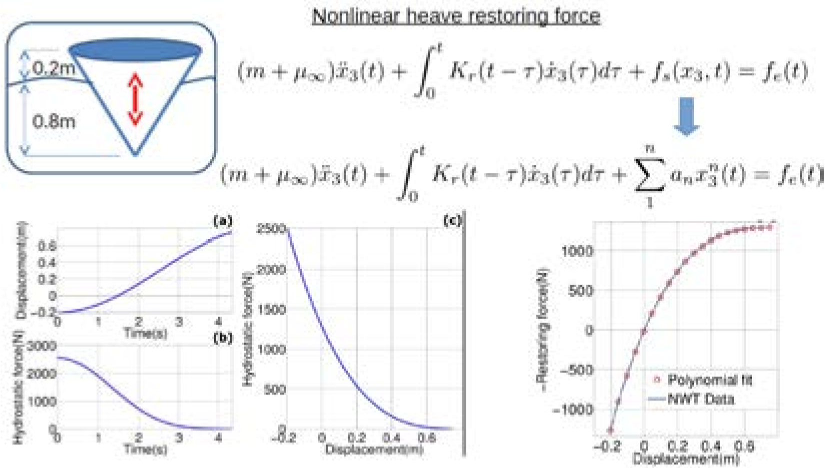


$$(m + \mu_\infty)\ddot{x}_3(t) + \int_0^t K_r(t-\tau)\dot{x}_3(\tau)d\tau + f_s(x_3, t) = f_e(t)$$

$$(m + \mu_\infty)\ddot{x}_3(t) + \int_0^t K_r(t-\tau)\dot{x}_3(\tau)d\tau + \sum^{n} a_n x_3^n(t) = f_e(t)$$

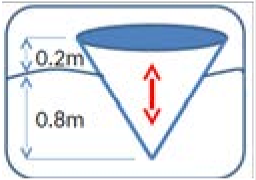


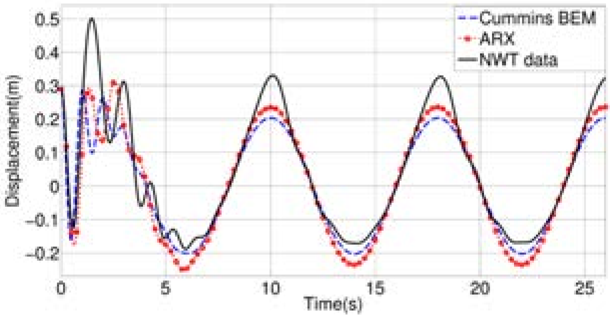
[1] Davidson, Giorgi and Ringwood, *Numerical wave tank identifcation of nonlinear discrete time hydrodynamic models*, 1st RENEW Conference, 2014



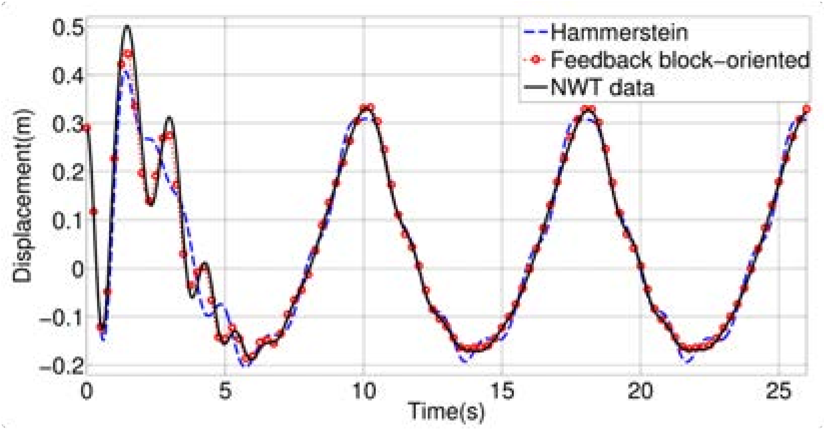
[1]Davidson, Giorgi and Ringwood, *Numerical wave tank identifcation of nonlinear discrete time hydrodynamic models*, 1st RENEW Conference, 2014

Sinusoidal input PTO force : Amplitude 960N

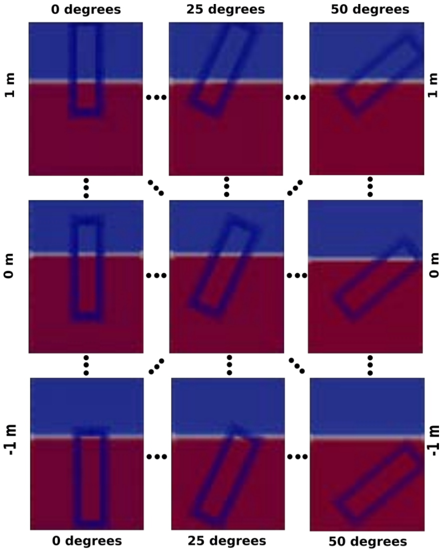




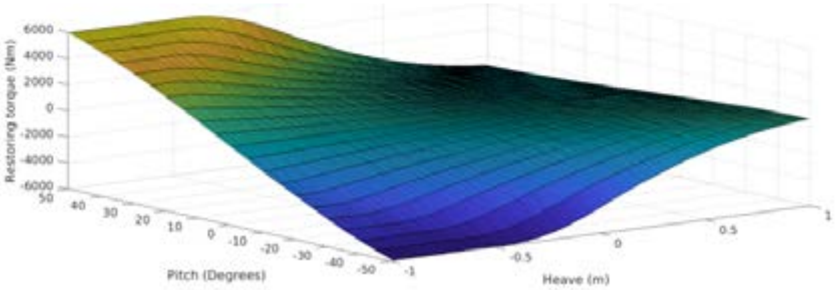
[1] Davidson, Giorgi and Ringwood, *Numerical wave tank identifcation of nonlinear discrete time hydrodynamic models*, 1st RENEW Conference, 2014



[1] Davidson, Giorgi and Ringwood, *Numerical wave tank identifcation of nonlinear discrete time hydrodynamic models*, 1st RENEW Conference, 2014

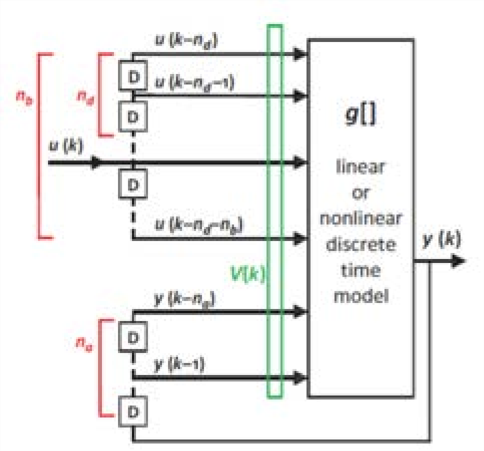


[1] Davidson, Karimov, Szelechmann, Windt and Ringwood, *Dynamic mesh motion in OpenFOAM for WEC simulation*, 14th OpenFOAM Workshop, 2019



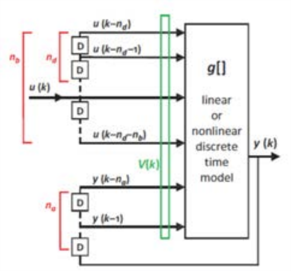
[1] Davidson, Karimov, Szelechmann, Windt and Ringwood, *Dynamic mesh motion in OpenFOAM for WEC simulation*, 14th OpenFOAM Workshop, 2019

Nonlinear Autoregressive with eXogenous terms (NARX)



[1] Giorgi, Davidson and Ringwood, *Identification of Wave Energy Device Models From Numerical Wave Tank Data?Part 2: Data-Based Model Determination*, IEEE Transactions on Sustainable Energy, 2016

Nonlinear Autoregressive with eXogenous terms (NARX)

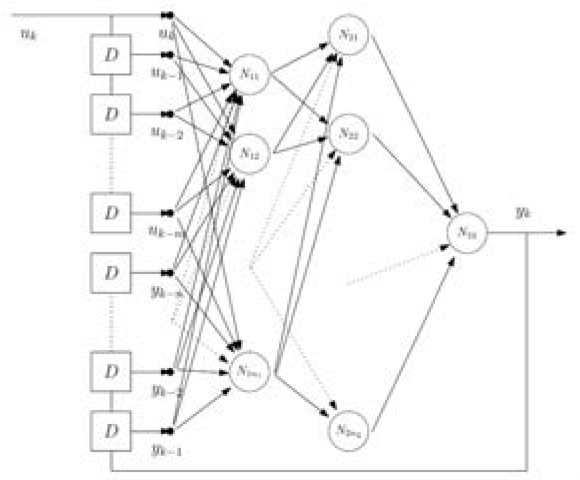


ARX

$$y(k) = \sum_{i=1}^{n_a} a_i y(k-i) + \sum_{i=0}^{n_b} b_i u(k-n_d-i).$$

[1] Giorgi, Davidson and Ringwood, *Identification of Wave Energy Device Models From Numerical Wave Tank Data?Part 2: Data-Based Model Determination*, IEEE Transactions on Sustainable Energy, 2016

Artificial Neural Network (ANN)



[1] Ringwood, Davidson and Giorgi, *Optimising numerical wave tank tests for the parametric identification of wave energy device models*, OMAE, 2015

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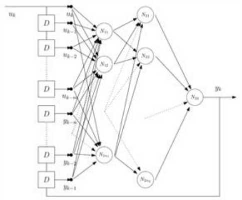
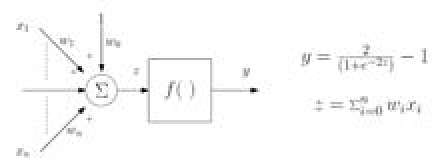
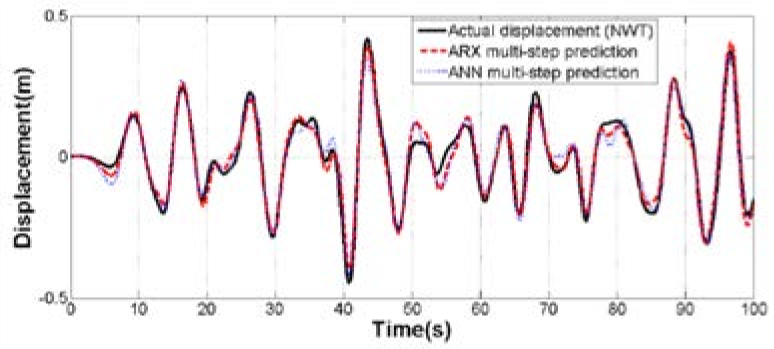


ANN



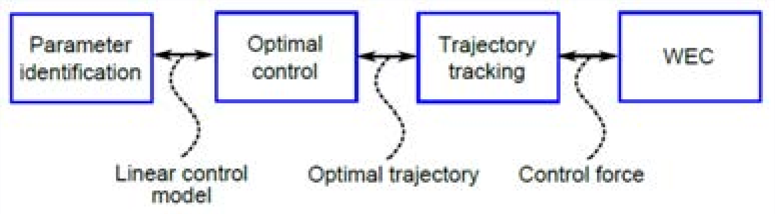
[1] Ringwood, Davidson and Giorgi, *Optimising numerical wave tank tests for the parametric identification of wave energy device models*, OMAE, 2015

Results



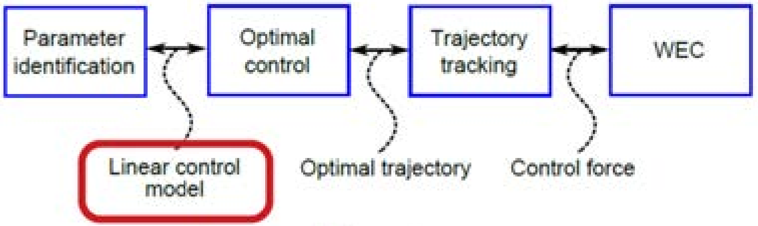
[1] Ringwood, Davidson and Giorgi, *Optimising numerical wave tank tests for the parametric identification of wave energy device models*, OMAE, 2015

Adaptive control



[1] Davidson, Genest and Ringwood, *Adaptive control of a wave energy converter simulated in a numerical wave tank*, EWTEC, 2017

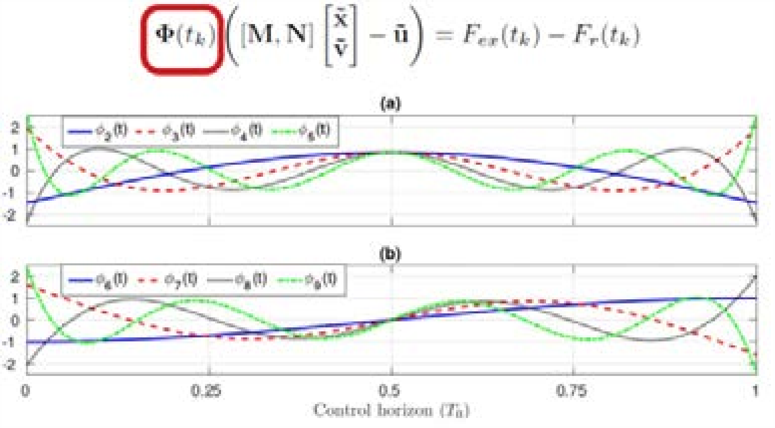
Linear control model



$$\Phi(t_k)\left([\mathbf{M},\mathbf{N}]\begin{bmatrix}\tilde{\mathbf{x}}\\ \tilde{\mathbf{v}}\end{bmatrix}-\tilde{\mathbf{u}}\right)=F_{ex}(t_k)-F_r(t_k)$$

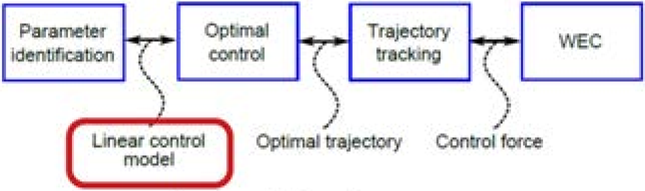
[1]Davidson, Genest and Ringwood, *Adaptive control of a wave energy converter simulated in a numerical wave tank*, EWTEC, 2017

Basis functions



[1] Genest, Davidson and Ringwood, *Adaptive control of a wave energy converter*, IEEE Transactions on Sustainable Energy, 2018

Optimisation



$$\Phi(t_k)\left([\mathbf{M},\mathbf{N}]\begin{bmatrix}\tilde{\mathbf{x}}\\ \tilde{\mathbf{v}}\end{bmatrix}-\tilde{\mathbf{u}}\right)=F_{ex}(t_k)-F_r(t_k)$$

The optimal controller maximises the absorbed energy, J, over the control horizon, I:

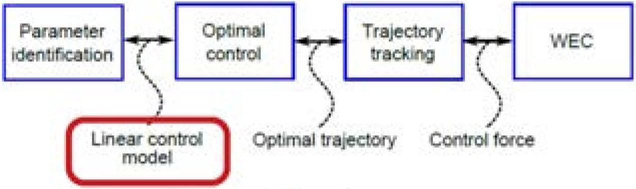
$$J=-\int_I v(t)u(t)dt$$

[1]Davidson, Genest and Ringwood, *Adaptive control of a wave energy converter simulated in a numerical wave tank*, EWTEC, 2017

NWT Experiments

System Identification - Example: Online Identification

Optimisation



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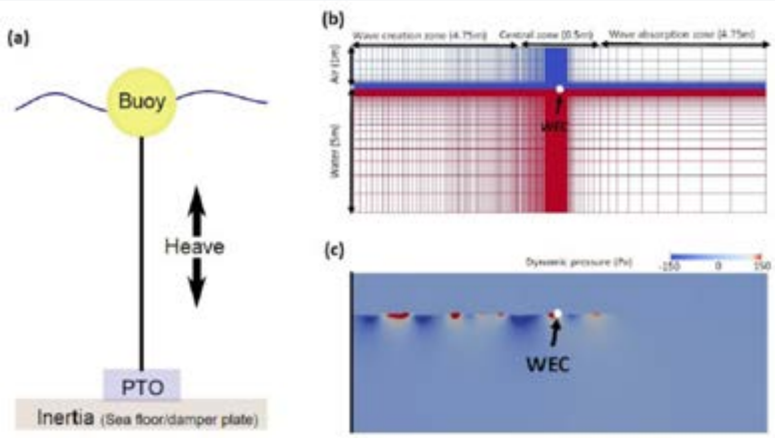
The optimal controller maximises the absorbed energy, J, over the control horizon, I:

$$J=-\int_I v(t)u(t)dt$$

$$J\ \propto\ -\tilde{\mathbf{v}}^T\tilde{\mathbf{u}}$$

[1] Davidson, Genest and Ringwood, *Adaptive control of a wave energy converter simulated in a numerical wave tank*, EWTEC, 2017

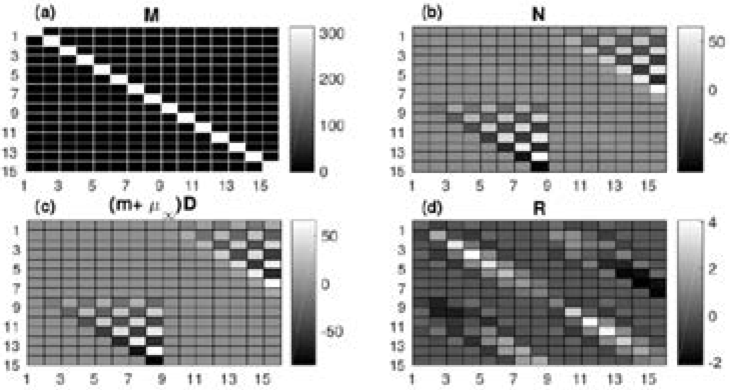
Case study



[1] Davidson, Genest and Ringwood, *Adaptive control of a wave energy converter simulated in a numerical wave tank*, EWTEC, 2017

Model parameters

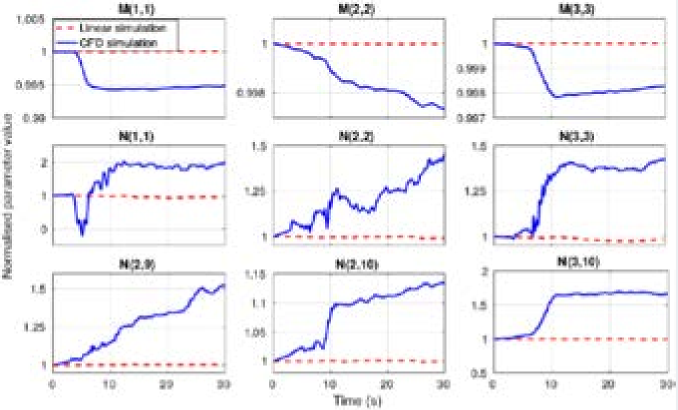
$$\Phi(t_k)\left([\mathbf{M}, \mathbf{N}]\begin{bmatrix}\tilde{\mathbf{x}}\\ \tilde{\mathbf{v}}\end{bmatrix} - \tilde{\mathbf{u}}\right) = F_{ex}(t_k) - F_r(t_k)$$



[1] Genest, Davidson and Ringwood, *Adaptive control of a wave energy converter*, IEEE Transactions on Sustainable Energy, 2018

Parameter adaptation

$$\Phi(t_k)\left([\mathbf{M},\mathbf{N}]\begin{bmatrix}\tilde{\mathbf{x}}\\ \tilde{\mathbf{v}}\end{bmatrix}-\tilde{\mathbf{u}}\right)=F_{ex}(t_k)-F_r(t_k)$$



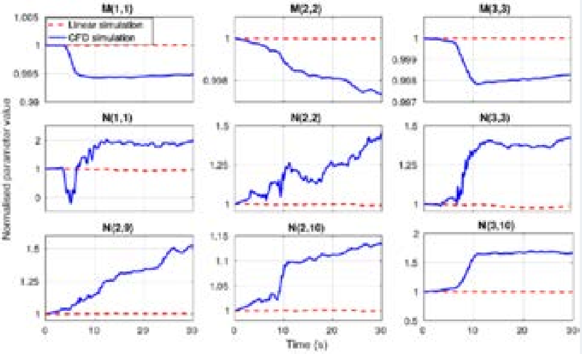
[1] Genest, Davidson and Ringwood, *Adaptive control of a wave energy converter*, IEEE Transactions on Sustainable Energy, 2018

Question

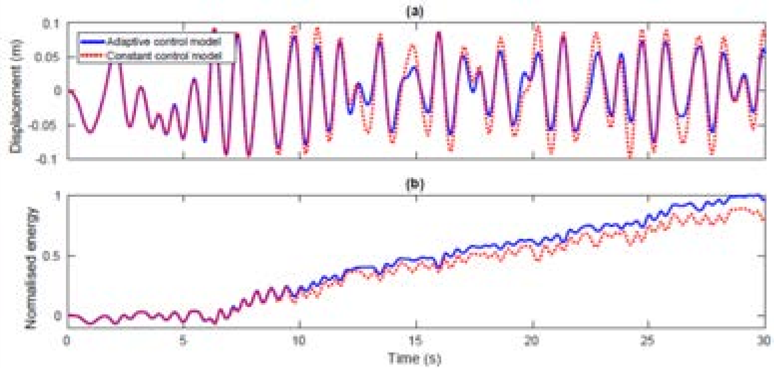
Why does the magnitude of the parameters in the M matrix decrease due to the online identification?

Parameter adaptation

$$\Phi(t_k)\left([\mathbf{M}, \mathbf{N}]\begin{bmatrix}\tilde{\mathbf{x}} \\ \tilde{\mathbf{v}}\end{bmatrix} - \tilde{\mathbf{u}}\right) = F_{ex}(t_k) - F_r(t_k)$$



Results

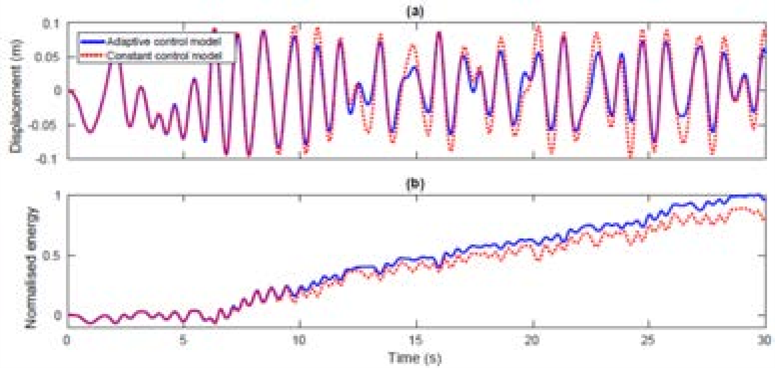


[1] Genest, Davidson and Ringwood, *Adaptive control of a wave energy converter*, IEEE Transactions on Sustainable Energy, 2018

Question

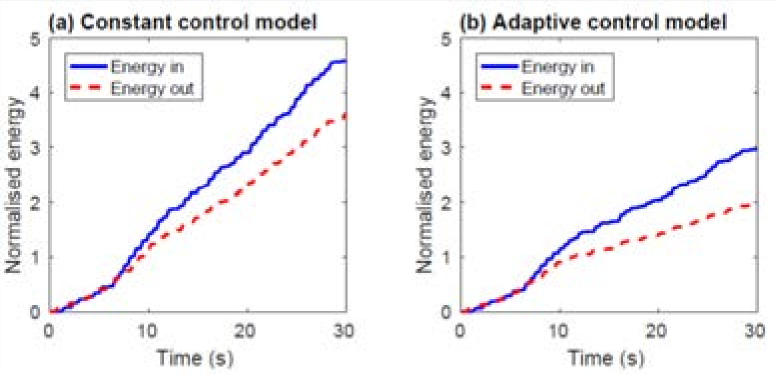
Why does the trajectory in the adaptive control simulation have a smaller amplitude than in the constant control model simulation?

Results



[1] Genest, Davidson and Ringwood, *Adaptive control of a wave energy converter*, IEEE Transactions on Sustainable Energy, 2018

PTO Energy Flow



[1] Genest, Davidson and Ringwood, *Adaptive control of a wave energy converter*, IEEE Transactions on Sustainable Energy, 2018

Conclusions

- Extensive design iteration and optimisation at low TRL levels is vital for the successful development of a MRE device
- NWTs are a valuable tool in the successful development of a MRE device
- A range of methods are available with a trade-off between accuracy and computational expense
- Modern day computing power allows the use of RANS CFD for an increasing variety of applications
- Different methods have strengths/advantages and the best choice may be case dependent, or could involve a combination of methods
- Growing Opensource communities are reducing barriers to NWT development
- When analysing a MRE in a NWT it is important to consider the entire system, with the complete energy flow from input resource to output power.
  - A chain is only as strong as its weakest link
  - Using low fidelity models for subsystems may negate the gains in accuracy acheived by computationally expensive models in other parts of the system
- NWTs offer significant advantages in the range of experiments and measurements available